

# Detection of Weak Gravitational Waves by Interferometric Methods and Problem of Invertible Calculations

A. I. GOLOVASHKIN, G. V. KULESHOVA, A. M. TZHOVREBOV  
*P. N. Lebedev Physics Institute, Moscow*

G. N. IZMAILOV, TRAN QUOC KHANH  
*Moscow Aviation Institute (a State Technical University)*

## Abstract

The fundamental features of the detection of non-stationary undulatory perturbations of metrics based on the interference effects are considered. The advantage of the Aharonov-Bohm effect in superconductors for these purposes in comparison with the ordinary optical interference is demonstrated. Some circuitries of the interferometric detectors in order to be used with SQUID are suggested. The possibilities of lowering the noise temperature of the ultraweak signals detectors based on the analogy between the processes of high-sensitive measurements and the reversible calculations are discussed.

The question about the detectability and the possibility of principle to carry out in practice the recording of gravitational waves (GW) had been brought up for the first time in the works of Bondi [1] and Weber [2]. The Bondi's mental experiment (friction of the beads that are "pushed away by the perturbation of metric" under the action of GW, a prototype of the modern laser-interferometric detectors [3, 4]), as well as the Weber's real experiments [5] with the massive aluminum antenna, equipped with piezo-sensors, have implied an energy transfer of GW to the mechanical system. Before these authors represented their own statements, it has been proposed a recording method of GW [6], assuming the conversion of the wave energy into the elastic-strain energy of a body with magnetostrictive properties (fig. 1). The possibility of recording a magnetic response, caused by the deformation of a magnetostrictive sample, of the superconductive quantum interferometer (SQUID) has brought the high efficiency to the method. On the present-day sensitivity the SQUID's are capable to register  $10^{-7}\Phi_0 Hz^{-1/2}$ , where  $\Phi_0 \simeq 2.07 \times 10^{-15} Wb$  is the flux quantum. The basic estimations on the basis of the actual parameters of magnetostrictive materials have allowed us to think of the possibility of enhancing the sensitivity of the proposed method in terms of GW metric tensor oscillation amplitude to the level of  $|\delta g_{ij}| \simeq 2.5 \times 10^{-23} Hz^{-1/2}$ .

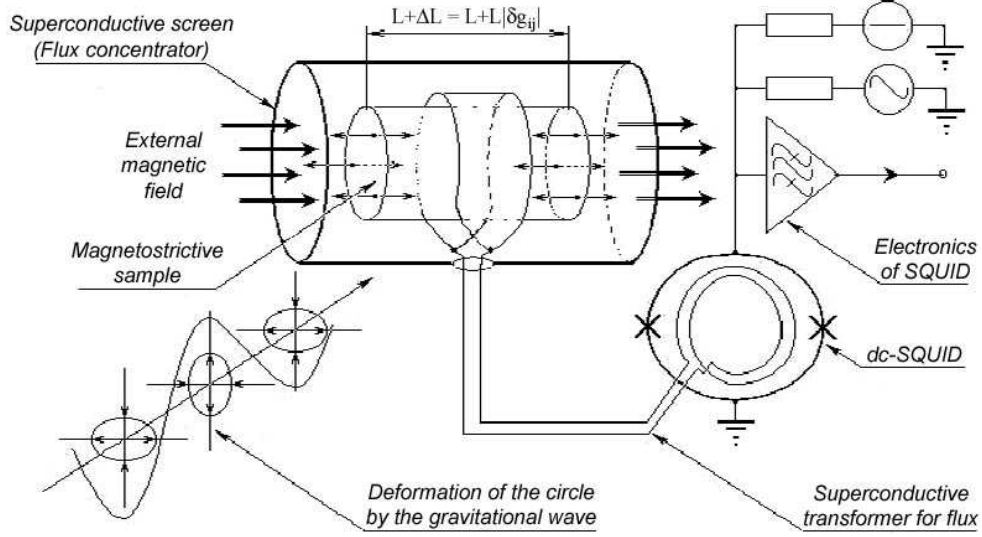


Figure 1. A method for the detection of GW that transforms the energy of GW into the energy of elastic deformation of a magnetostrictive sample.

The response from the magnetostrictor to the flux:  $\Delta\Phi = S\Lambda E|\Delta L/L|$ , where  $S = 200 \text{ cm}^2 = 2 \times 10^{-2} \text{ m}^2$  is the area of the base,  $\Lambda \gtrsim 2 \times 10^{-9} \text{ T/Pa}$  is the sensitivity, and  $E = 200 \text{ GPa}$  is the Young modulus of the magnetostrictor.

The resolution capacity of SQUID:  $\delta\Phi = 10^{-7}\Phi_0 (1/\sqrt{Hz}) = 2.07 \times 10^{-22} \text{ Wb}/\sqrt{Hz}$ . As  $\Delta\Phi$  is estimated by  $\delta\Phi \Rightarrow$  the sensitivity of the magnetostrictor in terms of the metric tensor variational amplitude:  $|\delta g_{ij}| = \Delta L/L = 2.5 \times 10^{-23} (1/\sqrt{Hz})$ .

However, when considering the recording processes based on the energy conversion of a GW field into the measurable signals, it must be taken into account that one out of the profound problems of the Einstein general relativity theory is the problem of determining the energy of the gravitational field itself [7, 8]. In particular, this problem comes up in the calculation of total energy fluxes transported by GW from a source. The divergences, arising at the same time about the simplest symmetries of the problem, have forced some authors [9] to deduce that GW, being purely “geometrical objects” themselves, in general do not transfer the energy. It is possible that the problems with the energy in physics of the nonstationary gravitation themselves are essentially original failures of the experimental detection of the gravitational radiation by the traditional methods. If this is really the case, then GW should be searched as nonstationary variations of metric by the direct approaches without transforming them into the vibrational energy of probe elastic bodies [5, 10] or the oscillations of the optical interferometer’s mirror [3, 4]. The direct measurement of the metric’s variations in interferometric experiments is possible due to measuring changes of the optical path difference, caused by the space-time

curvature under the action of undulatory gravitational perturbations, in the interferometer's arms. The arising phase difference periodically shifts the interference pattern, that leads to the change of a light intensity at the recording photomultiplier's input, and can be estimated in the end from the formula  $\delta\varphi = 2\pi L |\delta g_{ij}| / \lambda$ , where  $L$  is the interferometer's base length,  $\delta g_{ij}$  is the metric tensor's variation,  $\lambda$  is the operating wavelength of the interferometer. It is clear that in such experiments one should use in the interferometer the highly monochromatic light, because the monochromaticity holds down the error of the phase measurement. The radiation of ultrastable lasers meets this requirement. Because so far the X-ray lasers are not yet created and ultraviolet ones are not yet ultrastable, then the operating wavelength is still restricted below in the visible and near IR ranges (e.g., the high-stable infrared line of He-Ne laser [3]).

Though it is possible to reduce the operating wavelength (in order to increase the phase response capacity of an interferometric experimental system) by taking advantage of the quantum interference effect in weak coupling superconductors. The effective wavelength of the Cooper pairs' condensate, corresponding to the quantum interference in the geometry of the Aharonov-Bohm effect, is represented by formula  $\lambda_C = \pi\hbar/(eA)$ . For comparison with optics it is possible to write down the numerical value of the coefficient that relates  $\lambda_C$ , expressed in *angstrom* ( $\text{\AA}$ ), to the modulus of vector potential  $\mathbf{A}$ , expressed in *tesla* $\times$ *metre* ( $Tm$ ):  $\lambda_C [\text{\AA}] \approx 10^{-7} A^{-1} [Tm]$ . Consequently, even the technically attainable weak fields (with the orders of  $A \simeq 10^{-6} Tm = 1 \text{ } \mathcal{O}cm$ ,  $\lambda_C \simeq 0.1 \text{ } \mathcal{O}$ ) make the quantum interference of superconductive condensate (i.e. the Josephson effect and the Aharonov-Bohm effect) more preferred than optical interference on the terms of operating wavelength in experiments to detect the gravitational perturbations (when the base  $L$  of the interferometer is considerable). In order to unbind the interference systems from the restriction on their sensitivity, it is necessary to use the light that has not just the high monochromaticity and stability, but also the considerable power (about hundreds of *watts*) at the way in of the interferometers [4]. The last condition is imposed on the photoelectric multiplier, which otherwise will be unable accumulate any signal with the sufficient value of the signal/noise ratio even in the single-quantum counting regime. Under the very conditions of superconductivity the stability of parameters is ensured comparatively simply by freezing the magnetic flux, and in this case a critical current of high intensity is provided instead of an optical radiation of the required great power.

The principle of GW detection without converting the energy of waves into the oscillation energy of elastic samples in a certain sense is related to the issue on the possibility of information transfer without transferring energy. In our case, on the one hand, the problem to so general extent is not the issue, because the interferometric detection methods allow the indirect energy exchange. In interferometric detectors the GW "control" the phase. Being by itself nonlinear, such an effect permits the response energy to exceed the energy of the initiating perturbation. However, on the other hand, and in the most general formulation, the problem of transferring information with-

out transferring energy obviously permits an affirmative answer that involves directly the interferometric detection. This answer should be searched in the theory of reversible calculations on a quantum computer. As it is known, the reversibility on a quantum level [11] is made available by the fact that in the course of calculation the states are always transformed while they are still the proper states regarding the initial Hamiltonian of the problem. In this case the states may be degenerated according to energy.

In that way, the interference methods of detecting nonstationary variations of the metric appear, by implication, to be concerned with the theory of quantum computing. However, in this case it rather takes place the closer relation with namely reversible computations. In fact, the customary proposition, claiming that in order to process one bit of information it is needed to dissipate no less than  $kT$  of energy, refers to only the irreversible calculations. In reversible computations the “redundant” entropy is not produced. In this case, even in irreversible computations during the transformations the energy of the initial and final states of the system usually is still the same (two equal energetic minimum, separated by a potential barrier), but the dissipation of energy and/or the entropy growth is caused by the irreversibility of any transition from some initial state to a specified final state. It is clear that regarding such a transition a one-valued description of the inverse process is impossible indeed.

In essence, the simplest circuit [12] of reversible computations implies simply the preservation, during the computation, of all source data. It enables the computation to transform these data at any step, but the reversibility of calculation allows to exclude the dissipation. If to draw an analogy of the computations with measurements, then the main source of entropy, which is the necessities of prearranging at first a computer in the specified initial state, corresponds to an absorption of an idle frequency in super low-noise parametric amplifiers [13]. It is the inconvertibility of absorptive process of idle frequency results in the dissipation in parametric systems and does not allow to obtain here the “absolute zero” noise temperature. The generalization of the concept of transformation reversibility of system states simulating the computational process to a quantum level by the strategy construction of calculation is given, excluding the reduction of a wave function. Such is possible under transformations brought to operator activity on its eigenstates. In this case the uncertainty of eigenvalues becomes zero. Latter allows to draw an analogy of calculations on a quantum computer with measurements in parametric systems with a quantum squeezing.

More generally, the computation reversibility is achieved by the construction of such algorithm, when the column vector readings of computation result  $\vec{r}$  is received from the vector of input data  $\vec{e}$  via the transforming matrix  $\hat{M}$ , tolerating the construction of the inverse matrix  $\hat{M}^{-1}$ , so  $\vec{r} = \hat{M} \vec{e}$ , and/or  $\vec{e} = \hat{M}^{-1} \vec{r}$ . The reversible algorithms allow to produce the information processing without the increase of an entropy as of information, as thermodynamic. This means that on processing of one information bit is not

required to diffuse out the  $kT$  amount of energy. In this case it is possible to believe that the effective temperature of a computer is equal to zero.

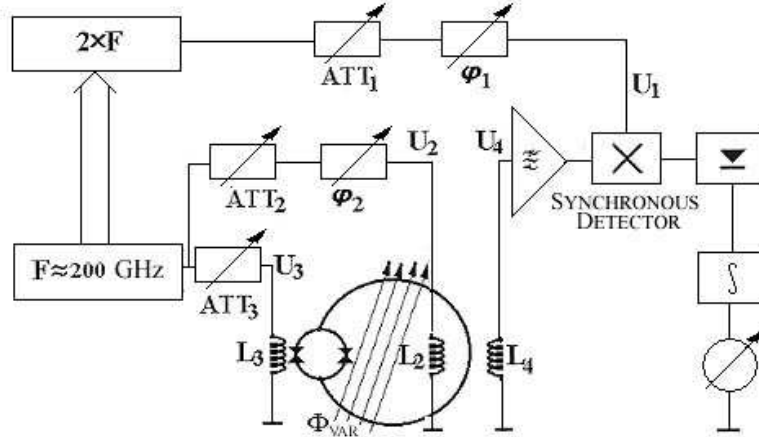


Figure 2. The circuit diagram of a dynamic squeezing anhysteresis UHF-SQUID.

It is apparent from the fluctuation-dissipative theorem, in the measurement process the final noise temperature reveals because of the nonzero imaginary part of ageneralized susceptibility of a system, that is due to the finite input resistance of a receiver. Namely the active resistance is responsible for the dissipation of the energy in measurements. This value in the full sense characterizes the irreversibility of the measurement process. The parallel between the computations and the measurements points of view points here on an advance possibility of the zero noise temperature, in case of possibilities to construct the algorithm reversible measurements. Clearly, such measuring receiver must be designed from pure-jet nonlinear elements. The parametric amplifier or the anhysteretic HF-SQUID's are the best on this role. In fig. 2 the flow-chart of the anhysteretic HF-SQUID with a quantum squeezing is given. The effect of which has been previously considered by authors of this message in the work [14]. In anhysteretic SQUID the role of nonlinear reactivity is played by the kinematic inductance of Josephson tunnel junction, under control of the outer magnetic flux, introduced in superconductive ring of SQUID. As an illustration of possible approaches on the creating of the technique reversible measurements let us consider an activity of the simplest three-frequency nondegenerate paramplifier with a nonlinear capacitance. The signal amplification here is achieved due to an insertion of a negative active component of an impedance on an input frequency. In this case the negative

active impedance arises solely due to mixing of three frequencies (the input, the idle and the pumping) on a nonlinear capacitance (fig. 3). Therefore, negative active component is obtained as a result of the work of purely reactive elements. At first glance, this system is not to comprise active resistances and according to the fluctuation-dissipative theorem may be characterized by the zero noise temperature. However, the parametric amplifier is not yet intended as the absolutely reversible measuring device. For its operation the absorbing load of the idler frequency is necessary. This resistive load makes different the noise temperature from zero. Consequently, the designing problem of parametric amplifier with the zero noise temperature or close to one is brought to the problem of development of the reversible dissipationless load.

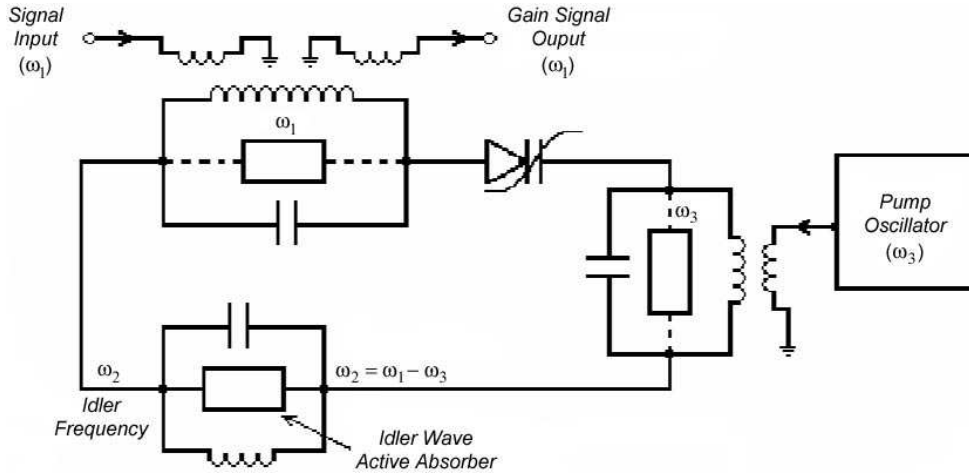


Figure 3. The schematic diagram of a simplest three-frequency non-degenerate parametric amplifier with a non-linear capacitance.

Here are three possible routes to solve the problem. The first one is analogous to the approach to reversible computations. In order to turn the process of information processing it is necessary to all the time to retain results of intermediate calculations. The latest asks the sufficient volume of the main memory. In this case one can produce only until for the storage of intermediate data memory there is an open place. Analogously, during the limited time, while in high-quality resonator does not end the transition processes, the initial processing can be regarded as dissipationless (or, more precisely, low dissipative) loading, while considering the Universe as an infinite-mode resonator without any time restriction needed for establishing the balance. On the other hand, it is possible simply to believe that the Universe has the quite low noise temperature as well as the load has. Indeed, until the forcing equilibrium has

not been made, the energy absorbed by the resonator is mainly putting in the growth of an oscillation amplitude, and it is not just dissipates in the form of the loss compensation for an oscillation period. Rather than to absorb the energy of an idler frequency in a resonator in the nonstationary regime, it could be radiate in outer space also, considering the Universe as the resonator with neither than unlimited time of equilibrium setting. On the other hand it is possible to simply believe that the Universe is a load with the rather low noise temperature. The second path of the dissipationless absorption is possible due to the reversibility property of a parametric amplifier itself. According to Manly-Row formula, it is easy to income in the condition of attenuation of input signal instead of amplification by means of the selection in a proper way of the relation between the working, the idle and pump frequencies. In such way, the parametric amplifier will be converted into the parametric load. As a result the circuit of the idler frequency of the fundamental amplifier must be linked with the input circuit of a parametric load. Such load is not intended as an absolutely dissipationless, because there must be the absorber “of its” idle frequency in the reversed amplifier. However, the noise temperature of a parametric load can be done below the physical temperature of the absorber. For a rough estimation of possibilities to lower one it is necessary to take the ratio of an input impedance of the parametric load and the impedance of the proper absorber of the idle frequency load. In this case the input impedance as a result of a corresponding circuit adjustment may be done however large. Really, one is a relation of an input voltage variation, corresponding to the increment of an input current, to the value of latter. The variation of an input voltage as the response of a nonlinear system on the current influence may be “made” the many times stronger than in linear case. On the role of the “third route” pretends the possibility of an interferometric suppression of a signal of the idler frequency (here is possible the analogy as with principle of coated optics, and with quantum computations too). For implementing of interferometric supressing the input signal needs to give on two equal parametric amplifiers with the combined pumping generator and inductively coupled loops of the idler frequency, which are geometrically located so that the magnetic fluxes in them became mutually antiphase.

It is obviously the use of principles of state squeezing in the quantum interferometer, recording the nonstationary variations of metrics, would allow us to increase considerably the receiver sensitivity of a GW signal. However this can be realized only after following upgrade of a measurement sensitivity on the basic principle of designing of the strategy of classical reversible measurements with zero (or vanishing) noise temperature. If to base on the finiteness of the energy flow rate across unit area by the transported GW and to use for its estimation the conventional formula of general relativity

$$S_G = c W_G = \frac{c^3 \omega^2}{16 \pi \gamma} \cdot (h_{yy}^2 + h_{yz}^2),$$

when it is clear the process of the energy transfer between a wave and the probe body of a classical receiver becomes “superunreversible”. Indeed, it is

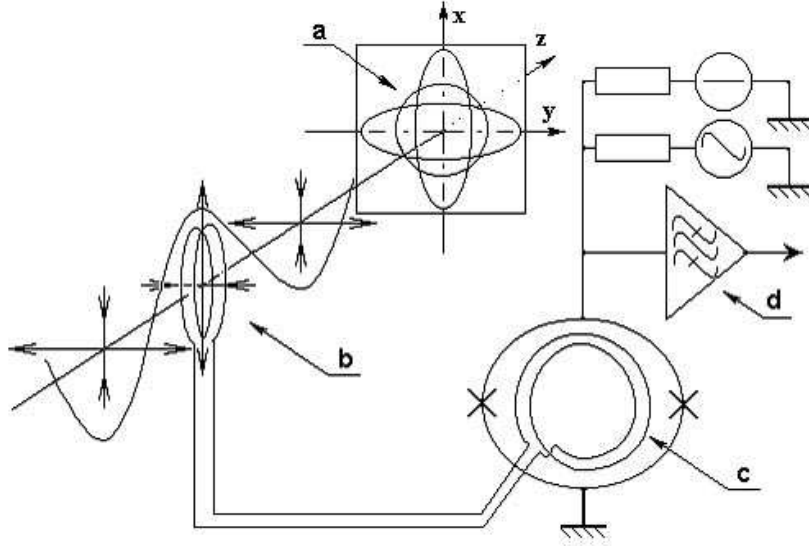
easy to compare the energy density in gravitational waves,

$$W_G = \frac{c^2 \omega^2}{16 \pi \gamma} \cdot (h_{yy}^2 + h_{yz}^2),$$

and in acoustical ones,

$$W_{Aq} = E \varepsilon^2,$$

when the variation amplitude of the metric tensor  $h_{ij}$  is equal to the amplitude of the specific elongation (strain tensor  $e_{ij}$ , Young modulus  $E \approx 5 \text{ GPa}$ ) of the elastic medium. At the frequency  $1 \text{ kHz}$  the ratio of energy density for these waves ( $W_G/W_{Aq}$ ) appears to be enormous, approximately  $10^{34}$ . It turns out that the empty Euclidean space possesses the huge elasticity; the effective Young modulus by the order of 34 is higher than at a “usual” matter.



*Figure 4.* The schematic diagram of the conversion of gravitational perturbations into the signals that are detectable by SQUID: **a** the distortion (“breathing”) of a circle, depicted inside a plane that is perpendicular to the wave vector; **b** the stretching of the effective area of the conversion coil in flux superconductive transformers; **c** the coupling coil that leads magnetic signals in DC-SQUID; **d** the input device from the electronic composition of DC-SQUID.

Such jump of the elasticity must generate the gigantic wave reflection on the boundary of matter-vacuum. By the same reason, the process of the energy

transfer from GW into mechanical oscillations is done much better than the inverse process. This very inconvertibility at the similar transformation (when others the less fundamental noise sources will be obviated) will not eventually allow us to bring nearer the noise temperature of the GW detector to absolute zero and makes meaningless the next step – the application of the quantum squeezing in the recording system evidently. The way out from such fundamental deadlock is the application of described above recording systems without direct energy conversion. In these ones the conversion irreversibility is lacking. The direct conversion of a gravitational perturbation into a phase response that SQUID is able to trap may be carried out by a superconductive transformer of the magnetic flux (fig. 4). The transformer is a closed superconductive circuit, which is composed from a couple of coils, each of them has an inductance value which is very close to the other's one: the conversion coil (fig. 4, b) and the coupling coil (fig. 4, c). The *coupling* (or *loop*) coil leads changes of the magnetic flux, generated by GW, to the “sensitive” element of SQUID. The *conversion* coil is put in such a way as to arrange the plane of its own rings to be parallel to the wave vector of perturbed GW. In such a configuration (fig. 5), according to Stokes theorem, any variation of the metric tensor  $g_{ij}$  may cause some change of the trapped magnetic flux that flows through the conversion coil circuit (i. e. through the plane XOZ, fig. 5):

$$\delta\Phi = \delta \oint g_{ij} A^i dr^j \approx \oint \delta g_{ij} A^i dr^j,$$

where  $A^i$  are the components of vector potential  $\mathbf{A}$ ,  $dr^j$  are the components of radius-vector  $\mathbf{r}$ ; the integral is taken along the whole closed contour of superconductive conversion coil, which lies in the plane XOZ. Therefore, any perturbation of the metric causes some small increment of the magnetic flux, whose (approximately) half will fall into the transmission coil. It is well known that when passing through the “ordinary” three-dimensional space, a plane gravitational wave incidents so that the circle, represented in the plane XOZ (fig. 5, a), which is perpendicular to the wave vector, is periodically stretched in one direction and squeezed in another direction (as it were “breathing”) while it leaves the area of the visible ellipse constant all the time. The stretching/shrinkage of the ellipse's axes, as well as of all linear dimensions inside the plane XOZ which is perpendicular to the wave propagation direction, leads to the change of the conversion coil's working area (while the wave vector is parallel to the planes of its rings), and this fact allows us to estimate the flux increment without need of calculating any circulation integral. The relative stretching/shrinkage of the ellipse's sizes is estimated approximately by the variation of the metric tensor. Consequently, the relative increments of the conversion coil's effective area and the magnetic flux are estimated by that one. Therefore, if in the transformer one freezes a magnetic flux  $\Phi_C \simeq 20 \text{ mWb} \approx 10^{13} \Phi_0$ , where  $\Phi_0 = 2.07 \times 10^{-15} \text{ Wb}$  is the flux quantum, then a gravitational wave whose amplitude of the metric tensor's oscillation is in the order of  $|\delta g_{ij}| \simeq 10^{-20}$  will give at the input of SQUID a flux increment of order  $\Delta\Phi \approx \Phi_C |\delta g_{ij}| \simeq 10^{-7} \Phi_0$ , that complies with the limit resolution of a modern two-stage DC-SQUID, which is in the order of  $0.1 \text{ Hz}$  [15].

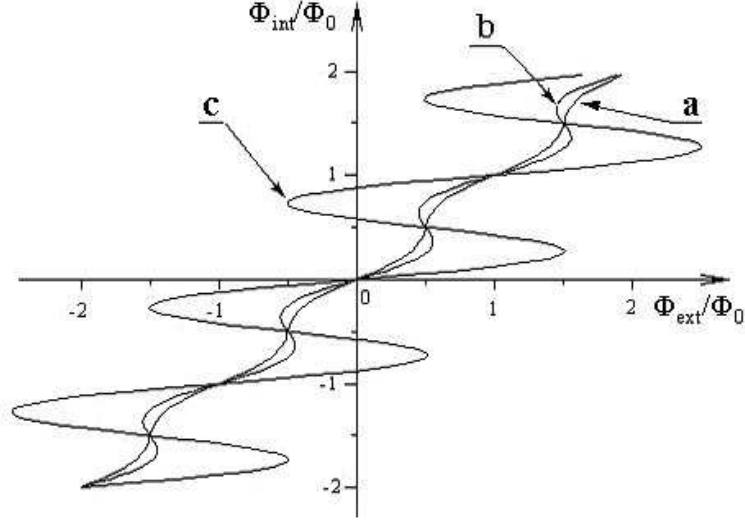


Figure 5. The plots that represent the dependence of the internal magnetic flux ( $\Phi_{int}$ , as the ordinate axis) inside a superconductive loop, switching into the circuit the Josephson tunnel transmission and functioning as an active transformer: **a** singlevalued anhysteresis loop; **b** multiplevalued hysteresis loop; **c** “utrahysteresis” loop.

According to our estimations, the design of terra-hertzian anhysteresis UHF-SQUID's using the quantum squeezing (fitting with Josephson plasmic oscillations) of coherent states is promising to increase the sensitivity by more than three orders (i.e. with  $\Delta\Phi \approx 10^{-10} \Phi_0$ ). At the same time it becomes available the detection of GW with the amplitude of order  $|\delta g_{ij}| \simeq 10^{-23}$  in the band of  $1\text{ Hz}$ . It is necessary to note that in the quoted estimations we have not yet taken in to account the signal losses, unavoidable when adjusting the SQUID's input circuit with the transmission coil (these losses are estimated to be of order 12). Based on the principle of the reversibility of linear electrodynamic systems, it is possible to offer a circuit for directly converting the variations of a gravitational field into phase responses, by means of utilizing an active superconductive transformer for the fluxes which includes the Josephson tunnel transition. In that case flux and phase are dependent on each other, but the linearity is still ensured by the smallness of the variations. The functions of the conversion and connection coils in an active transformer are integrated on the principle “two in one”, and the tunnel transition is put into the gap of the superconductive loop. The described structure is essentially a “superhysteresis” HF-SQUID, i.e.  $LI_C \gg \Phi_0$ , where  $L$  is the coil inductance,  $I_C$  is the critical current intensity of Josephson tunnel transmission. The wide

range of the multivalued hysteresis branch ( $\pm LI_C$ ) is in compliance with the small value of the derivative  $d\Phi_{int}/d\Phi_{ext} \approx \Phi_0/(LI_C)$  outside the vicinities of the points with  $\Phi_{int} = (n + \frac{1}{2})\Phi_0/2$  (in the linear domain); here  $\Phi_{int}$  is the internal magnetic flux through a loop,  $\Phi_{ext}$  is the external flux, and  $n$  is an integer. The internal flux  $\Phi_{int}$  (represented by ordinate axis in fig. 5) is determined by the phase difference in Josephson transmission,  $\Phi_{int} = \Phi_0$ . In response to the distortion of the metric in the closed circuit of an active transformer, it is brought about an increment of just the phase difference, that leads to the change of the internal flux [16]. The variation of the last, according to the principle of reversibility, has to result in an increment of the external flux which is proportional to  $(d\Phi_{int}/d\Phi_{ext})^{-1}$ . Consequently,

$$\partial\Phi_{ext} \approx (LI_C/\Phi_0) \Phi_{int} |\delta g_{ij}| \approx (LI_C/\Phi_0)^2 \Phi_0 |\delta g_{ij}|.$$

Otherwise, in terms of the flux quantum, the response of the external magnetic field on the dynamical variation of the metric is given by the expression  $\Delta\Phi_{ext}/\Phi_0 \approx (LI_C/\Phi_0)^2 |\delta g_{ij}|$ .

In order to estimate the limit resolution of the set-up in terms of metric instead of  $\Delta\Phi_{ext}/\Phi_0$ , it is necessary to set the resolution by the flux through SQUID, which is registering the external field, generated by an active transformer in response to the space-time distortion  $|\delta g_{ij}| \approx (\Delta\Phi/\Phi_0)/(LI_C/\Phi_0)^2$ . If by way of  $LI_C$  to take  $20 \mu Wb = 10^9 \Phi_0$ , then even at the sensitivity of SQUID  $\Delta\Phi/\Phi_0 \simeq 10^{-6} Hz^{-1/2}$  the set-up will be able to detect GW with the record-breaking small amplitude  $|\delta g_{ij}| \simeq 10^{-24} Hz^{-1/2}$ .

## References

- [1] H. Bondi, *Nature*, 179, 1072 (1957).  
H. Bondi, F. A. E. Pirani, I. Robinson, *Proceedings of the Royal Society*, A251, 519 (1959).
- [2] J. Weber, *Phys. Rev.*, 117, 306 (1960).
- [3] S. N. Bagaev, A. S. Dychkov, V. P. Chebotaev, *Pis'ma v JETP*, 33-2 (1981), pp. 85-88.
- [4] M. Coles in *Proc. Int. Conf. on Gravitational Waves: Sources and Detectors eds.*  
I. Ciufolini and F. Fedecaro in *World Scientific*, Singapore (1997).  
A. Giazotto in *Proc. Int. Conf. on Gravitational Waves: Sources and Detectors eds.*  
I. Ciufolini and F. Fedecaro in *World Scientific*, Singapore (1997).  
S. Kawamura and N. Mio in *Proc. 2nd TAMA Intern. Workshop on Gravitational Wave Detection*, Tokio Universal Academy, Tokio (1999).  
ACIGA, <http://www.anu.edu.au/ACIGA/>.
- [5] J. Sinsky and J. Weber, *Phys. Rev. Lett.*, 18, 795 (1967).

- [6] *Pis'ma v JETP*, 60-8 (1994), pp. 595-599.
- [7] W. Pauli, *Theory of Relativity* (1983).
- [8] J. Weber, *General Relativity and Gravitational Waves*, N.Y. (1962).
- [9] C. Müller in *Max Plank Festschrift*, S. 139, Berlin (1958).  
 L. Infeld in *Ann. Phys.*, 6, 341 (1959).  
 A. E. Scheidegger in *Rev. Mod. Phys.*, 25, 451 (1953).  
 N. Rosen in *Jubilee of Relativity Theory*, Basel (1956).
- [10] ALLEGRO, <http://sam.phys.lsu.edu/>  
 AURIGA, <http://www.lnl.infn.it/>  
 EXPLORER,  
<http://www.roma.infn.it/rog/explorer/explorer.html>  
 NAUTILUS,  
<http://www.lnf.infn.it/esperimenty/rog/NAUTILUS/>  
 NIOBE, <http://www.gravity.pd.uwa.edu.au/publ/niobe.html>
- [11] R. Feynman, *Found. Phys.*, 16 (1986), pp. 507-531.
- [12] C. H. Bennett, *Logical Reversibility of Computation*, *IBM J. Res. Devel.*, G (1979), pp. 525-532.
- [13] F. N. H. Robinson, *Noise and Fluctuations in Electronic Devices and Circuits*, Oxford University Press (1974).
- [14] A. I. Golovashkin, G. V. Kuleshova, A. M. Tzhovrebov in *Proc. of MIFI Conference* (in Russian), MIFI, Moscow (2003).
- [15] J. Clarke, *IEEE Trans. El. Dev.*, ED-27, 1896 (1980).
- [16] Bryce S. DeWitt, *Phys. Rev. Lett.*, 16, 1092 (1966).  
 G. Papini, *Phys. Lett.*, 24A, 32 (1967).